REPORT DOCUMENTATION PAGE

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1. AGENCY USE ONLY (Leave Blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
		Final Progress Report
		May 1, 2001 - January 31, 2004

4. TITLE AND SUBTITLE	5. FUNDING NUMBERS
Quantum computing with quasiparticles of the Fractional Quantum Hall Effect	DAAD19-01-1-0511

6. AUTHOR(S)

Dmitri Averin

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)	8. PERFORMING ORGANIZATION REPORT NUMBER
The Research Foundation of SUNY, Stony Brook University, Stony Brook, NY 11794-3362	

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSORING / MONITORING AGENCY REPORT NUMBER
U. S. Army Research Office P.O. Box 12211 Research Triangle Park, NC 27709-2211	42385.2-PH-QC

11. SUPPLEMENTARY NOTES

The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy or decision, unless so designated by other documentation.

12 a. DISTRIBUTION / AVAILABILITY STATEMENT	12 b. DISTRIBUTION CODE
Approved for public release; distribution unlimited.	.

13. ABSTRACT (Maximum 200 words)

The focus of this project was the theoretical study of quantum computation based on controlled transfer of individual quasiparticles in systems of quantum antidots in the regime of the Fractional Quantum Hall Effect (FQHE). The work addressed the basic issues of operation of such FQHE qubits as well as related questions of physics of FQHE transport and topological quantum computation. The main parts of our effort were the studies of mechanisms of decoherence, design of single- and two-qubit operaions for FQHE qubits, quantitative description of quasiparticle tunnelling between the edges of FQHE liquids, and decoherence properties of some of the generic models of topological quantum computation. The basic conclusion of this project is that the FQHE qubits provide a realistic way of implementation of semiconductor solid-state quantum logic devices competitive with other types of semiconductor qubits. Non-trivial exchange statistics of FQHE quasiparticles should enable convenient realization of the two-qubit operations that does not require the control of the two-particle interaction. For quasiparticles with the non-abelian statistics, the topological nature of this statistics can provide additional stability against decoherence.

14. SUBJECT TERMS			15. NUMBER OF PAGES
Fractional Quantum Hall Effect, topological quantum computation,			
			16. PRICE CODE

17. SECURITY CLASSIFICATION OR REPORT	18. SECURITY CLASSIFICATION ON THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	**UNCLASSIFIED**	**UNCLASSIFIED**	**UL**

NSN 7540-01-280-5500

Problem studied

Quasiparticles of the Fractional Quantum Hall Effect (FQHE) possess non-trivial exchange statistics which can be used to perform quantum transformations of the wavefunction of the electron liquid in the FQHE regime. Manipulation of the quasiparticle trajectories needed to perform such transformations can be realized by localizing individual quasiparticles in a system of quantum antidots and controlling electrostatic potentials of these anidots. The goal of this project has been to investigate the suitability of this approach for development of quantum computing devices, and understanding of potential characteristics of such devices, most importantly, their decoherence properties. Development of quantitative description of quasiparticle transport in antidot qubits made it necessary to work on the theory of quasiparticle tunneling between the edges of the FQHE liquids. Topological nature of the quasiparticle statistics motivated the need for understanding of decoherence properties of generic schemes of topological quantum computation.

Summary of the results

1. Design of FQHE qubits based on adiabatic quasiparticle transport [1].

The simplest structure of the FQHE qubits that has been considered in this project consists of the two tunnel-coupled antidots, with information encoded by the position of a quasiparticle on one or the other antidot. When the double-antidot system is gate-voltage tuned near the resonance, the energy difference between the quasiparticle states localized at the two antidots is much smaller than the energy gap in the spectrum of the antidot-bound quasiparticle states. In this regime, the double-antidot system is equivalent to the two-state system (qubit). The quasiparticle states localized at the two antidots are the |0> and |1> states of the computational basis of the qubit. The gate electrodes of the structure can be designed to control separately the energy difference and the tunnel coupling of the qubit states.

The two-qubit gates can be constructed using the anyonic exchange statistics of the FQHE quasiparticles, as a results of which intertwining of the two quasiparticle trajectories in the course of time evolution of the two qubits realizes controlled-phase transformation with non-trivial value of the phase. Such a controlled-phase gate combined with the possibility of performing arbitrary singe-qubit transformations is sufficient for universal quantum computation. We demonstrated this explicitly by finding a combination of the controlled-phase gate with single-qubit gates that reproduces the usual controlled-NOT gate in the case of the most robust FQHE state with the filling factor $\nu=1/3$.

We have also analyzed parameters of the antidot qubits and gates and decoherence mechanisms in them. The two main decoherence mechanisms are the electromagnetic losses in the external gate electrodes and coupling to the edges of the electron liquid. The basic conclusion of this analysis is that the required antidot structures can be fabricated with the present-day fabrication technology and should reach levels of decoherence acceptable for quantum computation.

2. Two-terminal conductance of the FQHE edge [2,4].

FQHE quasiparticles are transferred through the antidot structures by tunneling to/from the edge states encircling the antidots and the edge states localized at external boundaries of the FQHE electron liquid. Although the description of edge states in terms of the chiral Luttinger liquids has been established for quite a long time, quantitative understanding of tunneling between the edges has many

problems. Under this grant, we have studied one of the most important unresolved problems in this area, the question of dc conductance of a simple FQHE edge coupled to external Fermi-liquid reservoirs with large number of electron modes. It was shown that in contrast to a regular (non-chiral) one-dimensional conductor, two-terminal dc conductance of the edge indeed acquires a fractional value. The intrinsic mechanism responsible for this is the flux attachment in the FQHE liquid which changes the branch of the fermionic statistics of electrons tunneling from the reservoir and is independent of energy relaxation.

3. Decoherence properties of the Majorana-fermion qubits.

Analysis of the decoherence properties of our basic scheme of the anidot qubits operating with abelian quasiparticles of the v=1/3 FQHE state has shown that that the topological nature of the exchange statistics of the two quasiparticles in this case does not provide additional barrier to decoherence. For abelian quasparticles, dynamic phase that is not protected by topology of the wavefunction of the FQHE liquid can not be separated from the statistical phase acquired by quasiparticles, and decoherence mechanisms affecting the quasiparticle dynamics suppress also the coherence of the statistical phase. This means that in abelian topological quantum computation the geometric origin of the statistical phase does not imply additional stability against decoherence.

This result does not apply directly to the case of quasiparticles with non-abelian exchange statistics for which overall dynamic phase does not directly affects transformations within the subspace spanned by the internal quasiparticle degrees of freedom. In this case effect of decoherence depends strongly on the nature of the typical coupling between the system and environment. Decoherence can be suppressed if the internal quasiparticle subspace corresponds to the fractionalized electron states that are spatially separated so that the external environment can not couple to an individual state. We have studied decoherence in a model of one-dimensional p-wave superconductor that has Majorana-fermion states of this type, and showed that the quality factor of the qubits based on these is a sensitive function of the details of the environment. In the large-temperature regime, the quality factor of the qubit operation in the topologically-protected regime is an exponential function of the quality factor of individual electrons, so that the topological nature of the qubit can indeed be helpful in suppressing the decoherence. However, such an exponential suppression does not take place in the more relevant low-temperature regime. As a next step, one should study the decoherence mechanisms typical for quasiparticles of the experimentally realizable FQHE state with filling factor v=5/2 (which should have similar fractionalized and spatially-separated Majorana-fermion states), in order to see whether the topological protection is effective against these mechanisms.

4. Strong-coupling theory of multi-point tunneling between different FQHE states [3,5].

Non-trivial exchange statistics of FQHE quasiparticles manifests itself in a crucial way in tunneling between different FQHE states, when the tunneling process is necessarily accompanied by conversion of the quasiparticles from the type characteristic for one FQHE state to another. We have developed the theory of multiple point-contact tunneling between the edges of different FQHE states in the non-perturbative regime of strong tunneling. Duality transformation of electron tunneling model determines the charge and statistics of quasiparticles that can be generated by weak backscattering at the contacts. Both the charge and statistics are given by the conductance matrix describing the branching of edge states in the absence of backscattering, and are in general different from those of quasiparticles in the bulk of the FQHE liquids. The obtained characteristics of quasiparticles can be used to calculate transport properties of the ``non-uniform'' antidots formed by the edges of FQHE states with different filling factors.

Publications

(a) Papers in referreed journals

1. D.V. Averin and V.J. Goldman, ``Quantum computation with quasiparticles of the Fractional Quantum Hall Effect'', Solid State Commun. **121**, 25 (2002).
2. V.V. Ponomarenko and D.V. Averin, ``Two-terminal conductance of a FQHE edge'', JETP Letters **74**, 87 (2001).
3. V.V. Ponomarenko and D.V. Averin, ``Broken symmetry, hyper-fermions, and universal conductance in transport through a fractional quantum Hall edge'', Europhys. Lett. **61**, 102 (2002).
4. V.V. Ponomarenko and D.V. Averin, ``Quantum coherent equilibration in multi-point electron tunneling into a fractional quantum Hall edge'', Phys. Rev. B **67**, 035314 (2003).
5. V.V. Ponomarenko and D.V. Averin, ``Strong-coupling branching between the edges of the Fractional Quantum Hall liquids'', Phys. Rev. B **69**, (2004); to be published.

(b) Conference proceedings

1. D.V. Averin and V.J. Goldman, ``Quantum computation with FQHE quasiparticles'', in: ``Electronic correlations: from Meso- to Nano-physics '', Ed. by T. Martin et al., (EDP Sciences, 2001), p. 551.
2. D.V. Averin and V.J. Goldman, ``Quantum computation with quasiparticles of the Fractional Quantum Hall Effect'', in: ``Future Trends in Microelectronics'', Ed. by S. Luryi et al., (Wiley, 2002), p. 334.

(c) Papers presented at meetings, but not published

1. V.V. Ponomarenko and D.V. Averin, ``Hyper-fermion statistics and universal conductance of a FQHE edge'', presented at:
   - APS March Meeting, March 2002, Indianapolis;
   - NATO ARW ``Theory of quantum transport in nanoscale devices'', June 2002, St. Petersburg, Russia.
2. V.V. Ponomarenko and D.V. Averin, ``Strong-coupling branching of FQHL edges'', presented at the APS March Meeting, March 2004, Montreal.

Scientific personnel

Professor Vladimir Goldman, Co-PI
Dr. Vadim Ponomarenko, Research Scientist
Mr. Aleksander Sobczyk, Graduate Student